Journal of the Royal Society of Western Australia, 92: 53–66, 2009

Northern Sources of the Leeuwin Current and the "Holloway Current" on the North West Shelf

N D'Adamo[1], C Fandry[2], S Buchan[2] & C Domingues[3]

[1] Perth Regional Programme Office of the UNESCO
Intergovernmental Oceanographic Commission,
1100 Hay Street, West Perth, WA, 6005.
✉ nick.d'adamo@bom.gov.au

[2] RPS MetOcean,
31 Bishop Street, Jolimont, WA, 6014.
✉ chris.fandry@metoceanengineers.com
✉ steve.buchan@metoceanengineers.com

[3] Commonwealth Scientific & Industrial Research Organisation,
Division of Marine and Atmospheric Research,
Castray Esplanade, Hobart, Tasmania, 7000.
✉ Catia.Domingues@csiro.au

Manuscript received November 2008; accepted February 2009

Abstract

This paper reviews the northern sources of the Leeuwin Current and related circulation on the North West Shelf, north of where it consolidates into its well-known poleward boundary current structure off North West Cape, Australia.

This review finds that relatively warm, low salinity waters enter the Indonesian-Australian Basin through two major remote northern sources. One is tropical Pacific Ocean water emanating from the South East Asian seas via the Lombok, Ombai and Timor Straits. The other is tropical northwest Indian Ocean water via the South Java Current within the 5–10° S zone off the Sumatra and Java coasts.

At the broadest scales, both sources undergo circuitous routes and associated evaporation and cooling before entering the head of the Leeuwin Current off North West Cape.

It is largely unresolved as to how close to the North West Shelf coast the Leeuwin Current's source waters flow. However, earlier oceanographic studies, supported by more recently collected data presented in this paper, indicate that at least during the low wind conditions of the Southern Hemisphere autumn, a reasonably well-defined, southwestward coastal flow occurs along the shelf and shelf break. An explanation previously suggested is that this current is driven by the steric height gradient produced by local surface heating, and we propose here to name it the Holloway Current in honour of the late Dr Peter Holloway.

Keywords: Leeuwin Current, North West Shelf, Indonesian Throughflow, Holloway Current.

Introduction

To provide the broad-scale context of this review, we begin by presenting a picture (Figure 1, adapted from Domingues *et al.* 2007) of the relevant major current systems known to operate in the southeast Indian Ocean. The key features to note in the northern portion are the Indonesian Throughflow via the Lombok, Ombai and Timor Straits, the semi-annually reversing South Java Current, the South Equatorial Current and the Eastern Gyral Current, which bifurcates north and south en route to northwest Australia. South of North West Cape, the prominent flows are the Leeuwin Current, Leeuwin Undercurrent, West Australian Current and South Indian Current.

Kronberg (2004) and Domingues (2006) describe the seasonal wind patterns over the region between northwest Australia and the Indonesian archipelago in the context of their importance to the hydrodynamics of the North West Shelf and adjacent Indonesian-Australian Basin region. The wind patterns are dominated by the changing monsoons: the Summer Monsoon (generally December-April) and Winter Monsoon (generally June–October) (Figure 2). West-southwesterly winds dominate during the austral summer (December–February). Winds then weaken to almost zero in March, to be followed by a weak to moderate April period and relatively strong east-southeasterlies associated with the well known Southeast Trade Wind pattern until about September. The winds then relax and turn again to the Summer Monsoon pattern. These wind patterns play a very important role in the dynamics of the underlying ocean by inducing Ekman flows which interact with the regional current systems. The interplay between Ekman induced and geostropically driven currents is an important feature.

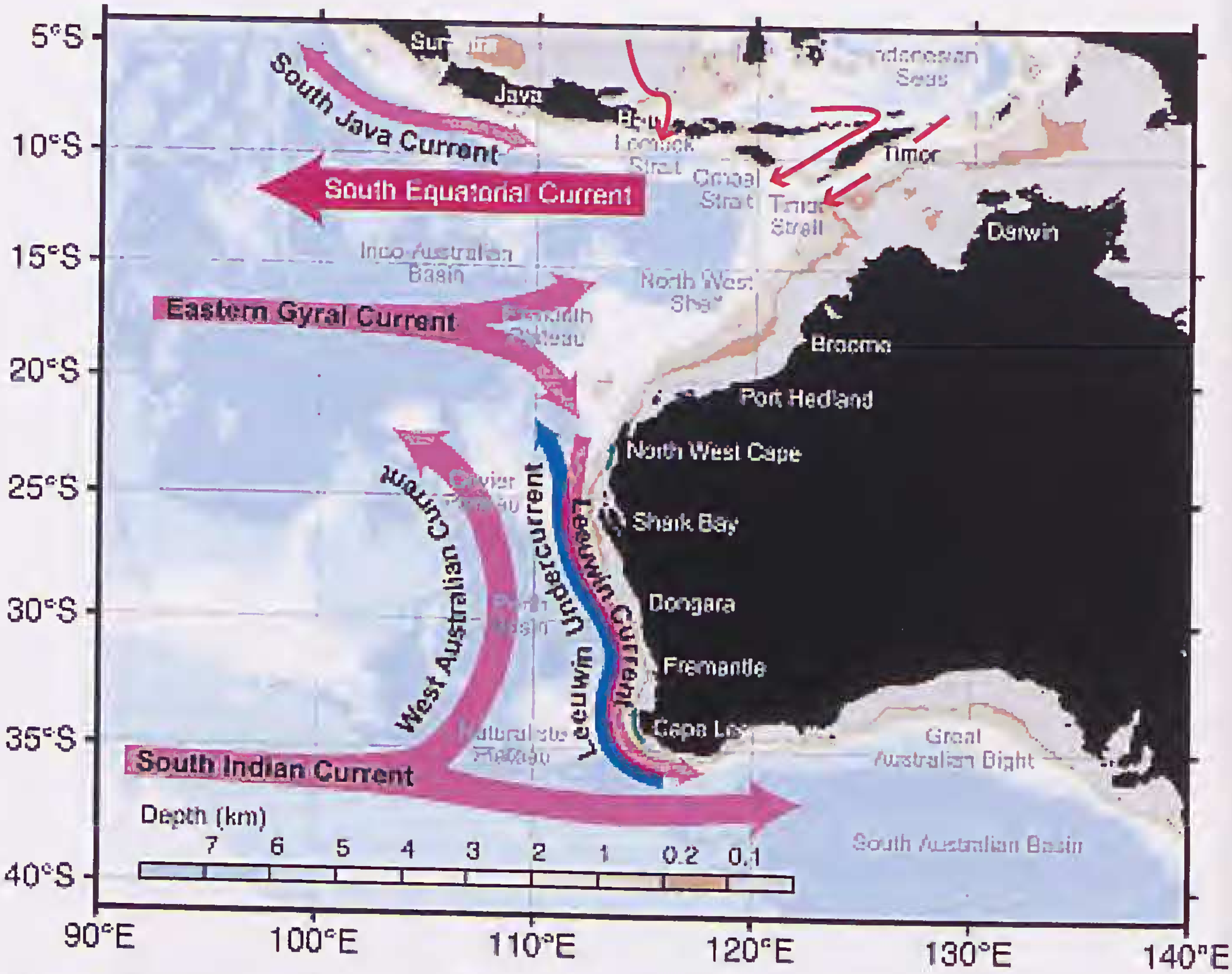


Figure 1. Major current systems in the southeast Indian Ocean, including the Indonesian Throughflow emanating from the Lombok, Ombai and Timor Straits. (adapted from Domingues *et al.* 2007).

This paper's focus is to review the northern sources of the Leeuwin Current and the circulation patterns of the North West Shelf that influence these sources en route to feeding the head of the Leeuwin Current off North West Cape. The sub-tropical sources (Domingues 2006) and Leeuwin Undercurrent (Thompson 1984, 1987; Smith *et al.* 1991; Pattiaratchi 2006; Domingues 2006) are not addressed in this paper.

Over 100 years ago, marine biologists postulated the existence of an eastern boundary current of tropical and sub-tropical water propagating southwards along the Western Australian coastline (Pearce & Cresswell 1985). Subsequently it has been found that this current turns eastward when it reaches the Southern Ocean and continues to flow along the southern Australian coastline until it reaches Tasmania, where it turns southwards to form the Zeehan Current (Ridgeway & Condie 2004). Domingues (2006) investigated where the Leeuwin Current derives its major sources of water, concluding that these are in the Indonesian Throughflow (tropical waters of Pacific Ocean origin), South Java Current (tropical waters of Indian Ocean origin) and sub-tropical waters in sub-surface intensified eastward jets of the sub-tropical Indian Ocean gyre. Kronberg (2004) examined aspects of seasonal circulation over the North West Shelf and its possible impact on the larger scale ocean circulation. Of particular interest was the origin of the seasonal maximum in the Leeuwin Current, which is observed around May. Pattiaratchi & Buchan (1991) and Feng *et al.* (2003) note that the broad scale drivers of the Leeuwin Current are subjected to ocean scale ENSO variability at inter-annual scales, with the current strengthening during La Nina years and weakening during El Nino years.

Leeuwin Current historical context

The Leeuwin Current is driven by a strong meridional pressure gradient, which is fundamentally established by the steric height difference between the relatively buoyant surface waters off northwest Australia and relatively denser (cooler and higher in salinity) surface waters off southwest Australia. This height difference is estimated to be as large as 0.5 m at its seasonal maximum (Pattiaratchi 2006). The Leeuwin Current flows poleward

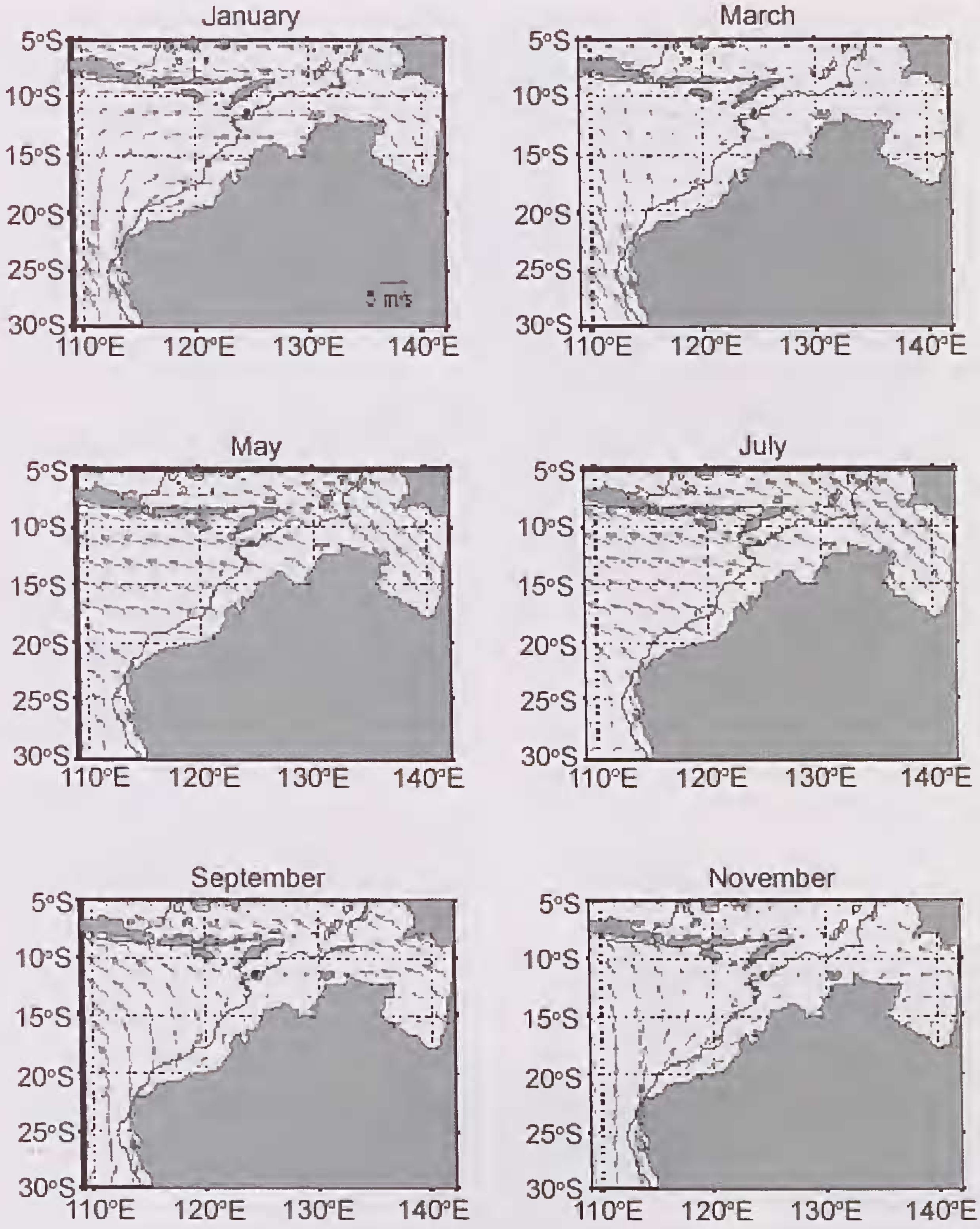


Figure 2. Major wind patterns over the North West Shelf and Indonesian-Australian Basin region (from Kronberg 2004).

despite, and in opposition to, prevailing equatorward winds off the coast. Godfrey & Ridgway (1985) examined the alongshore momentum balance between northwest and southwest Australia, indicating that the pressure gradient dominates in the austral autumn-spring, being at its strongest during May–June, and that northward winds dominate during spring-summer. Seasonal wind stress manages to modulate the Leeuwin Current, allowing it to be at its maximum strength in winter when opposing winds are at their weakest. In spring–summer, coastal winds drive opposing coastal counter currents of relatively high salinity and low temperature, confirmed at several locations, variously impeding or forcing the Leeuwin Current offshore (Rochford 1969; Cresswell & Golding 1980; Cresswell *et al.* 1985, 1989; Smith *et al.* 1991; Gersbach *et al.* 1999; Taylor & Pearce 1999; Pearce

& Pattiaratchi 1999; van Hazel 2001; Woo *et al.* 2006a,b; Pattiaratchi 2007; Akhir 2008; Woo & Pattiaratchi submitted). These counter currents are associated with sporadic upwelling and resulting coastally enhanced nutrient levels, phytoplankton biomass and primary production, as exemplified by Hanson *et al.* (2005) for the Ningaloo Current (Taylor & Pearce 1999) off North West Cape and reviewed generally for Western Australia by Pattiaratchi (2006). Notwithstanding this, the Leeuwin Current generally suppresses broad-scale coastal upwelling of the intensity that features off the other two equivalent continental west coastlines of the southern hemisphere (South America and South Africa) where colder, higher salinity equatorward coastal flows dominate throughout the year (Pearce 1991). As a result, although the prevailing wind regime is similar to the highly productive coastal waters of these other eastern ocean margins, the Western Australian coastal waters have relatively low nutrient levels and associated primary production, being oligotrophic by comparison (Pattiaratchi 2007).

The Leeuwin Current's capacity to carry tropically derived waters and associated biological propagules (Simpson 1991; Hatcher 1991) is responsible for the presence of a globally recognised and unique marine biodiversity hotspot (Roberts *et al.* 2002) off the central west coast of Western Australia, characterised by a mix of tropical and temperate species. It is also responsible for the presence of tropical species off the south coast of Western Australia. The Leeuwin Current is therefore a fundamentally important mechanism underpinning the marine biodiversity of the region. It also plays a strong role in local climate through its influence on sea surface temperatures and coupled atmospheric properties off the coast (Weaver 1990; Gentilli 1991; Pattiaratchi & Buchan 1991; Telcik 2004).

The Leeuwin Current begins its distinct flow as a coherent boundary current in the vicinity of North West Cape, at about 22° S. At this Leeuwin Current head region, it has typical properties of approximately 150 m deep, 0.5 m s^{-1}, 34.9 psu, 24 °C and 1023.6 kg m^{-3}, and is slightly more saline and cooler than the waters of the Indonesian Throughflow and South Java Current to the north (Domingues 2006). By the time it passes 34° S, the Leeuwin Current's properties undergo a transition to approximately 300 m depth, 1.5 m s^{-1}, 35.55 psu, 18 °C and 1025.7 kg m^{-3}, having been augmented by geostrophic inflows of sub-tropical Indian Ocean water (Domingues 2006; Godfrey & Weaver 1991). It is generally <100 km wide along its length and strongly meandering (Thomson 1984; Smith *et al.* 1991; Pearce & Griffiths 1991), regularly breaking out to sea in eddies and other associated dynamical instabilities (Waite *et al.* 2007). The Leeuwin Current signature extends from North West Shelf to Tasmania, forming the longest boundary current in the world (Ridgway & Condie 2004). Further details on the anatomy and dynamics of the Leeuwin Current can be found in Waite *et al.* (2007).

Northern sources of the Leeuwin Current

The major northern sources of the Leeuwin Current were reviewed and analysed by Domingues (2006) and Domingues *et al.* (2007). They used the 1994-96 WOCE ICM6 experiment observations at 22° S and numerically modelled tracking of particles (released in the upper 600 m of the Pacific and Indian oceans) from the 1/6 deg. Los Alamos National Laboratory Parallel Ocean Program model (POP11B) for the simulation period 1993–1997 (Figure 3).

This work was conducted in conjunction with reviews of past studies on associated volume transports of the Leeuwin Current's source waters and regional circulation patterns. It supports and supplements earlier studies (*e.g.*, Godfrey 1996; Bray *et al.* 1997; Potemra *et al.* 2002; Wijffels *et al.* 2002; Feng & Wijffels 2002; Wijffels &

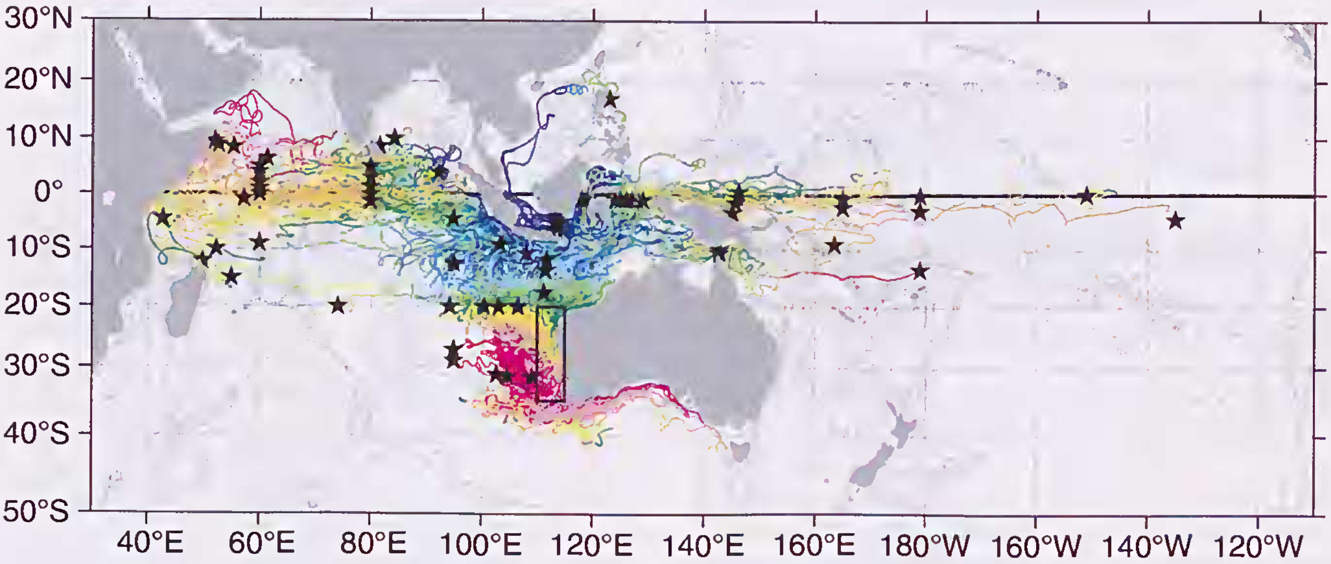


Figure 3. Northern tropical sources of the Leeuwin Current, as indicated by particle trajectories analysed by Domingues *et al.* (2007) from model output of the Los Alamos National Laboratory Parallel Ocean Programme run POP11B (1993-97). The stars represent particle trajectory release points (all with start depths < 600m). The coloured lines show the paths traversed by the particles. Different colours along the lines represent different salinities. The particles shown were those that found their way into the black box drawn off Western Australia, representing the Leeuwin Current.

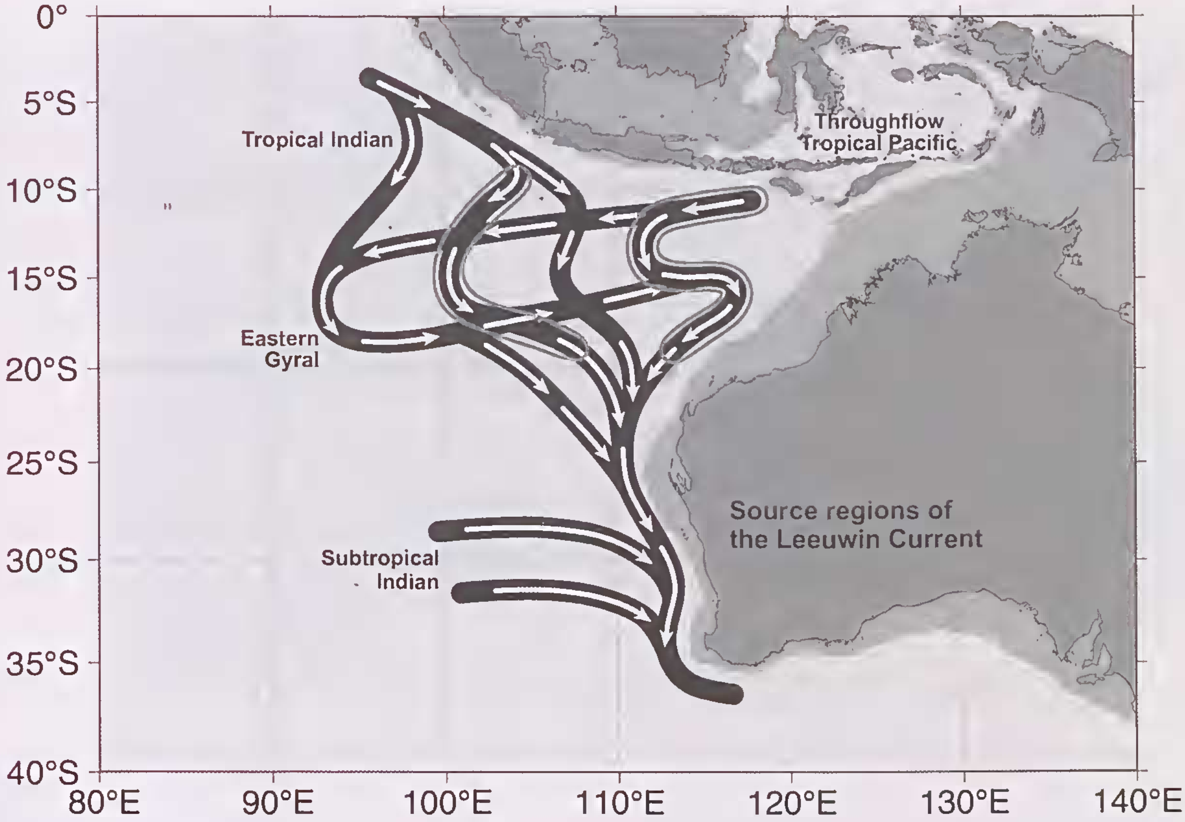


Figure 4. Schematic diagram (from Domingues *et al.* 2007) of the upper circulation of the southeast Indian Ocean near Australia associated with the source regions of the Leeuwin Current, as per the results of the Domingues *et al.* (2007) POP trajectory analyses in Figure 3.

Meyers 2004) in showing that the equatorial Pacific Ocean region provides a major northern source of water for the Leeuwin Current, carrying tropical Pacific Ocean water into the Indonesian-Australian Basin via the Lombok, Ombai and Timor Straits.

Domingues (2006) and Domingues *et al.* (2007) also used the POP model particle tracks to identify the other major northern source for the Leeuwin Current as the Indian Ocean, where tropical water is derived from between northeast Africa and Indonesia. Particles find their way to the head of the Leeuwin Current off North West Cape mainly via the South Java Current (Quadfasel & Cresswell 1992; Meyers *et al.* 1995), which is a boundary current that semi-annually reverses to flow prominently southeastward off Sumatra and Java around May to November. At these times, the South Java Current is principally a response to coastal and equatorial Kelvin waves, or Wyrtki Jets, (driving the Equatorial Counter Current) forced by westerly wind bursts during the monsoon transitions in the equatorial Indian Ocean (Wijffels *et al.* 1996; Sprintall *et al.* 1999). The other, lesser, source for the South Java Current is the Indian Monsoon Current that is locally generated by winds of the Indian Monsoon (Wijffels *et al.* 1996).

At the broadest scales, Domingues (2006) and Domingues *et al.* (2007) also investigated the pathways that these respective sources most likely follow en route to the head of the Leeuwin Current, concluding that both undergo circuitous routes and associated evaporation

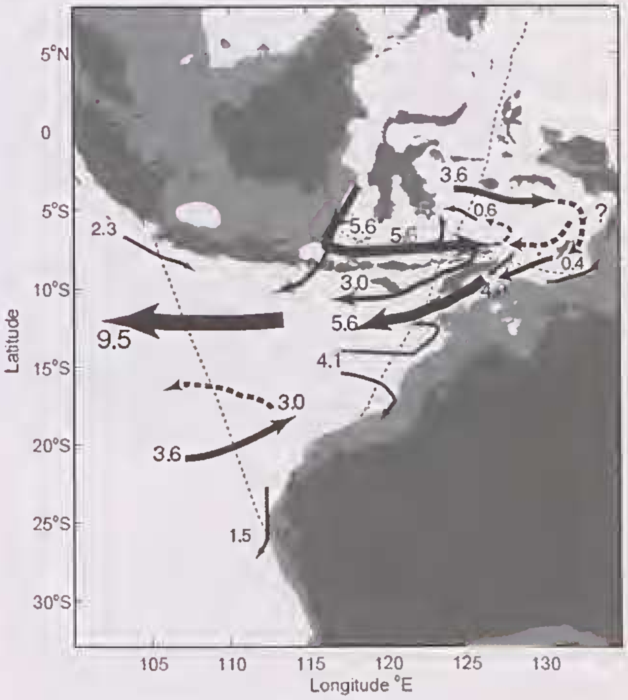


Figure 5. Wijffels *et al.* (2008) estimates of flow pathways and associated fluxes (Sv) for major currents of the Indonesian Throughflow and circulation of the Indonesian-Australian Basin, based on 20 years of XBT data collected along the dashed lines.

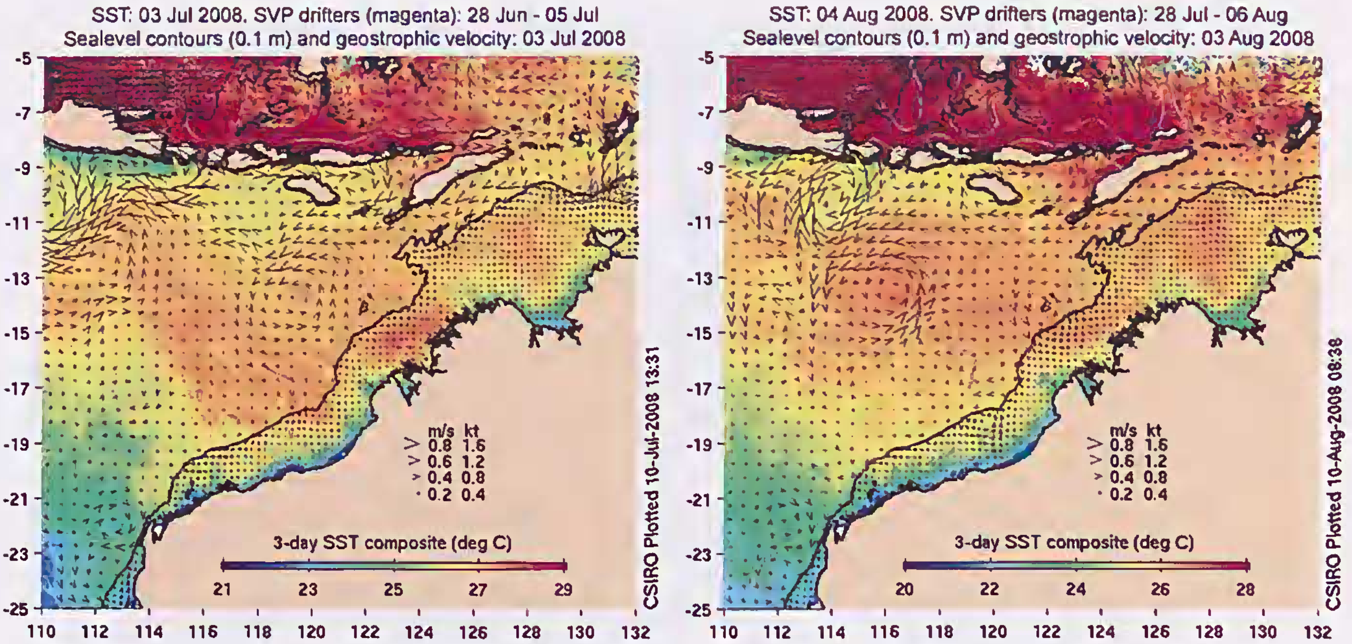


Figure 6. Satellite images for 3 July showing a very prominent eddy centred at about 120° E , 14° S which has moved westwards a distance of about 300km by 3 August 2008. This is equivalent to a westward propagation speed of 10 km day^{-1} or 0.1 m s^{-1}.

and cooling before passing North West Cape (Figure 4). In the upper 100 m of the water column, some of the water that emerges from the Indonesian Throughflow joins the westward flowing South Equatorial Current (south of the Indonesian Archipelago), within the 10–15° S zone. The flow geostrophically traverses that current and becomes part of the southern branch of the Eastern Gyral Current, which flows eastward within the 15–20° S zone. As the Eastern Gyral Current approaches the northwest coast of Australia, it bifurcates north and south, with the southern branch feeding the head of the Leeuwin Current.

Two other characteristic pathways for the source waters are ones that emanate from the Indonesian Throughflow and the other from the South Java Current, with Domingues *et al.* (2007) referring to them as the direct offshore "C" route and indirect onshore "S" route respectively. All pathways meet on the North West Shelf and become a surface poleward boundary flow which is strongest from April to July. The idea that the Leeuwin current is supplied with waters directly from the Timor Strait is not supported by the modelled particle tracks, but this may be as a result of a model bias that overestimates the flow rate passing through Ombai Strait (Domingues 2006)

The mean geostrophic velocity and transport associated with the Indonesian Throughflow were examined by Wijffels *et al.* (2008) on the basis of 20 years of eXpendable BathyThermograph (XBT) data. Their schematic (Figure 5) provides a recent assessment of the various volume fluxes associated with the main currents in the region

Circulation on the North West Shelf

There appear to be very few observational, numerical or analytical studies addressing the detailed dynamical characteristics associated with the overall progression of Indonesian Throughflow and South Java Current waters through to the head of the Leeuwin Cuurent (Domingues *et al.* 2007). As such, this aspect of the dynamics of the region is yet to be accurately resolved. Some studies have analysed satellite altimeter data to discern eddy features in the region. For example, Feng & Wijffels (2002) suggest the occurrence of important baroclinic instability features in the South Equatorial Current zone, which draw their energy from the available potential energy associated with the Throughflow. The eddies are typically 150–200 km in diameter with current speeds in the range 0.4–0.8 m s^{-1}. They propagate westwards at speeds of up to 0.2 m s^{-1} and remain coherent over 40–80 day periods. An inspection of satellite images for the region of interest shows that these eddies are nearly always present. A typical example is shown in Figure 6. Bray *et al.* (1997) examined WOCE and JADE hydrographic observations, in conjunction with TOPEX/POSEIDON altimeter data, finding westward propagating features between 8° S and 13° S, generally consistent with those reported by Feng & Wijffels (2002). The eddies were simulated by Nof *et al.* 2002, using analytical models which support the idea that they are caused by a baroclinic instability mechanism.

Further south in the latitude band 20°–30° S, Fang & Morrow (2003) described the characteristics of eddies originating in the Leeuwin Current, again using TOPEX/POSEIDON altimeter data. In the period 1995 to 2000 they tracked 37 warm, long-lived eddies, some travelling west a distance of 2500km at speeds ranging from 0.02 to 0.15 m s^{-1}. In the process, they transfer low-density Indonesian Throughflow and Leeuwin Current source waters, into the southeast Indian Ocean. Most of these eddies are spawned during the period May – June, when the Leeuwin Current is most intense, suggesting an instability mechanism perhaps triggered by topographic features.

Although previous observations over the North West Shelf have been relatively limited and spatially

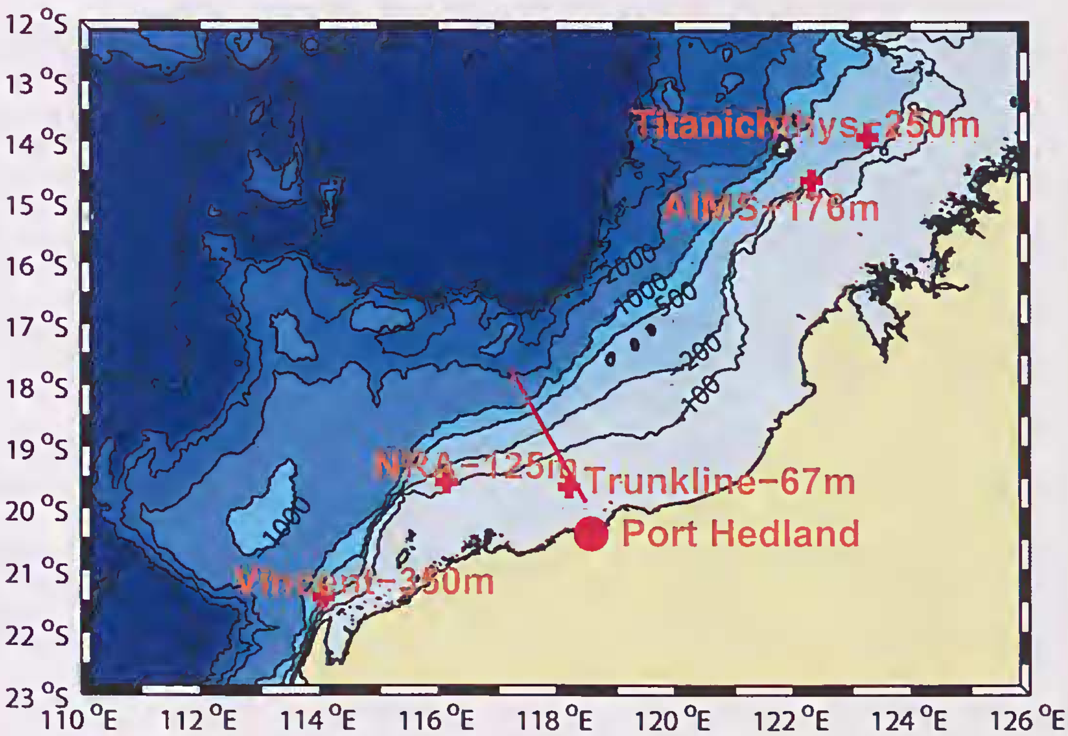
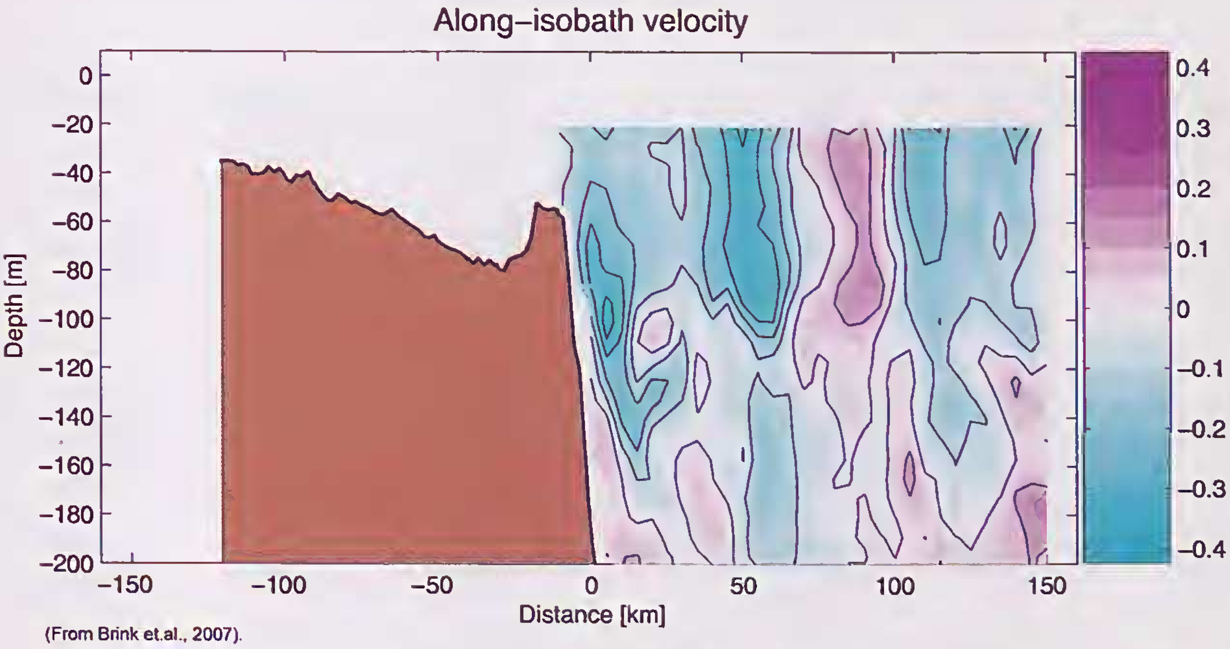


Figure 7. Current meter locations over and adjacent to the North West Shelf of Australia (courtesy of RPS MetOcean on behalf of Inpex Browse Ltd, Woodside Energy Ltd (Perth) and the Australian Institute of Marine Sciences (AIMS)). Also shown is the CTD and ADCP transect (red line) of Brink *et al.* (2007).



(From Brink et.al., 2007).

Figure 8. Alongshore current at the transect shown in Figure 7 representative of the flow in June- July, 2003.

constrained, the measurements analysed by Holloway & Nye (1985) nonetheless suggest a propensity for flow over this shelf to be a potentially important contribution to the Leeuwin Current. Holloway & Nye (1985) analysed 19 months of current meter data (1982/83) collected over the North West Shelf in water depths between 40 and 260 m in the region 114.5–116.5° E and 19.5–21.2° S. Reasonably strong southwestward flow was evident, being strongest during February-July of both years and stronger than could be accounted for by wind stress alone. Holloway & Nye (1985) reasoned this to be the Leeuwin Current on the North West Shelf driven by steric height gradient in opposition to wind stress, consistent with the ideas of Godfrey & Ridway (1985). Holloway & Nye (1985) also noted the occurrence of weak upwelling events in both summer and winter

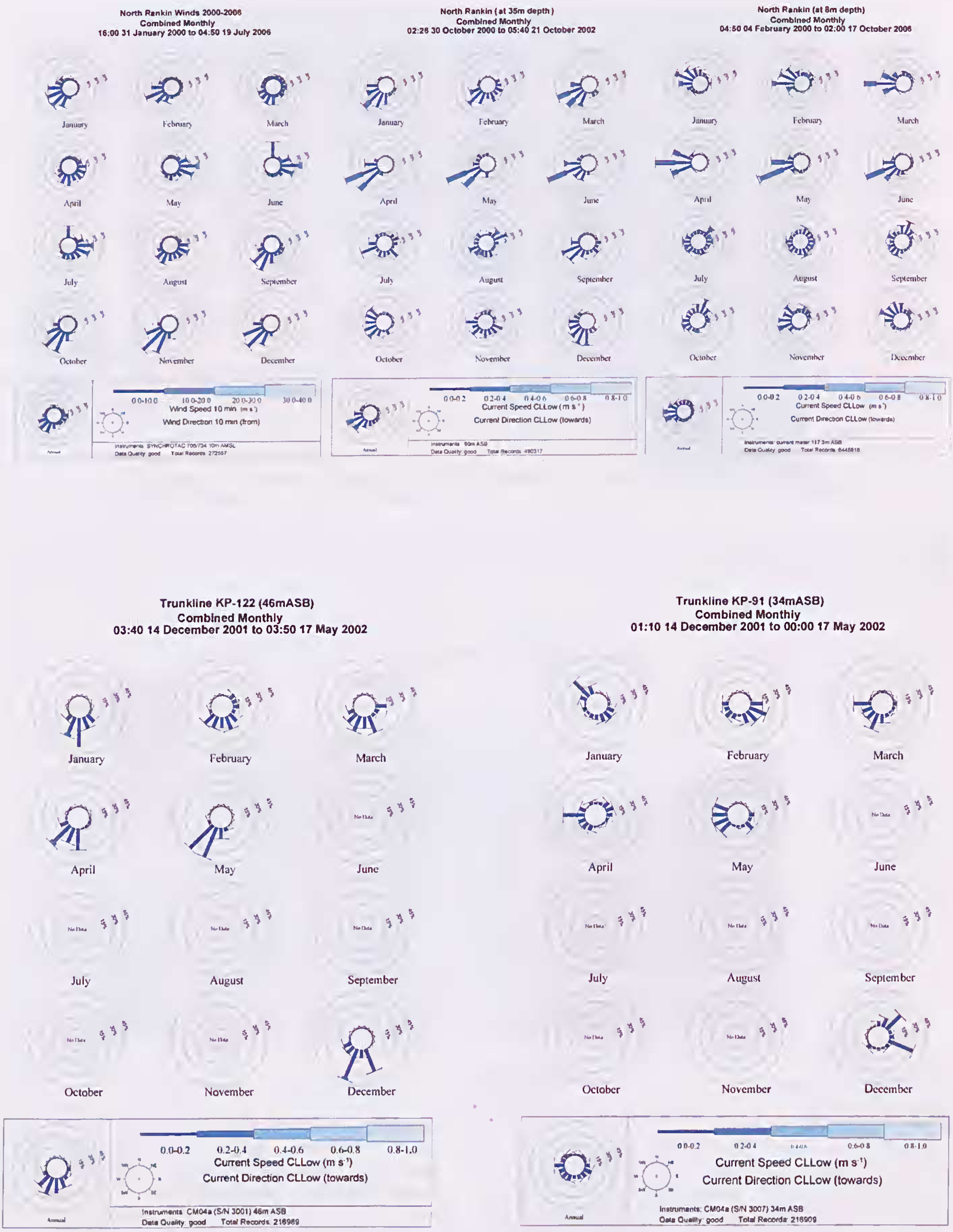
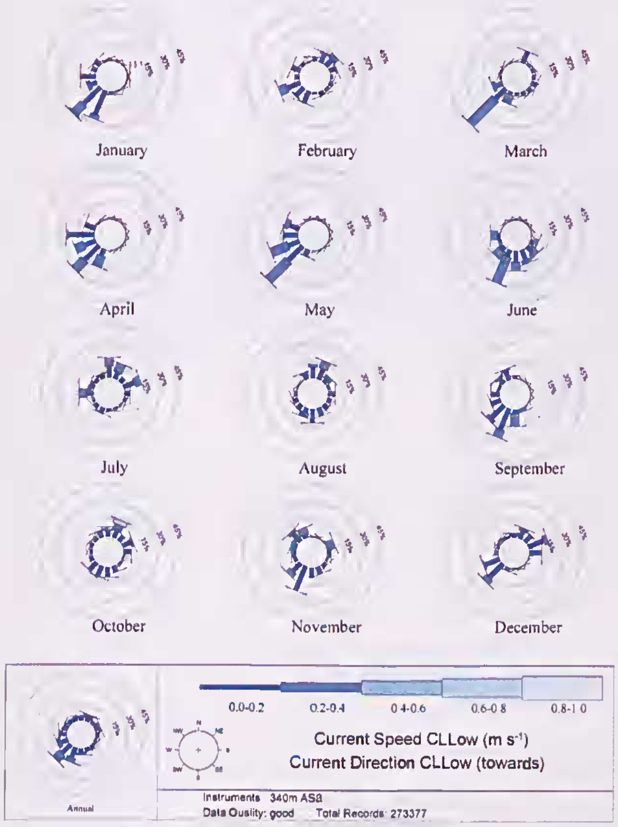
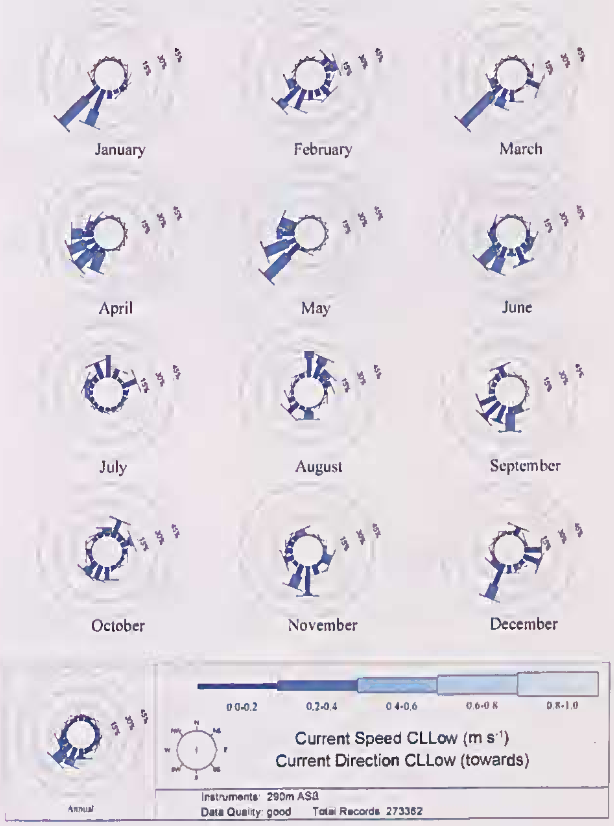


Figure 9. Combined monthly averaged current meter for data collected at the sites shown in Figure 7. For North Rankin, monthly averaged wind roses (directions from which wind is blowing) are also presented, showing winds predominantly from the southwest during September–February, and then weakening in March to April/May.

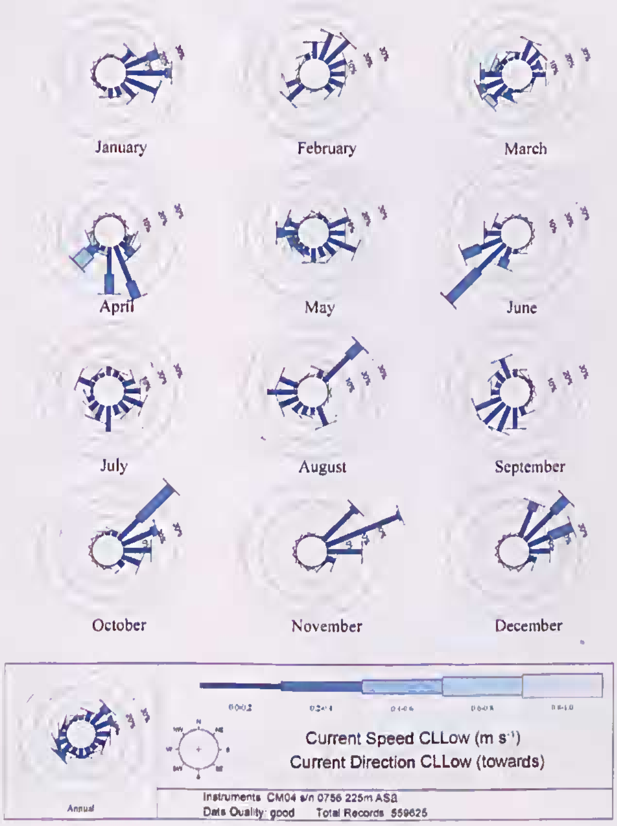
Vincent (at 10m deep)
Combined Monthly
05:00 21 November 2000 to 08:50 13 December 2001



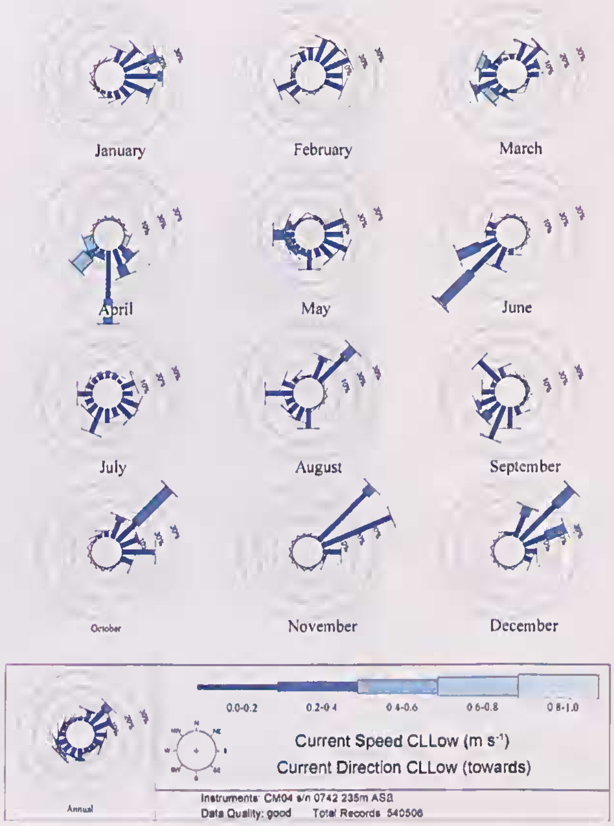
Vincent (at 60m deep)
Combined Monthly
05:30 21 November 2000 to 08:50 13 December 2001

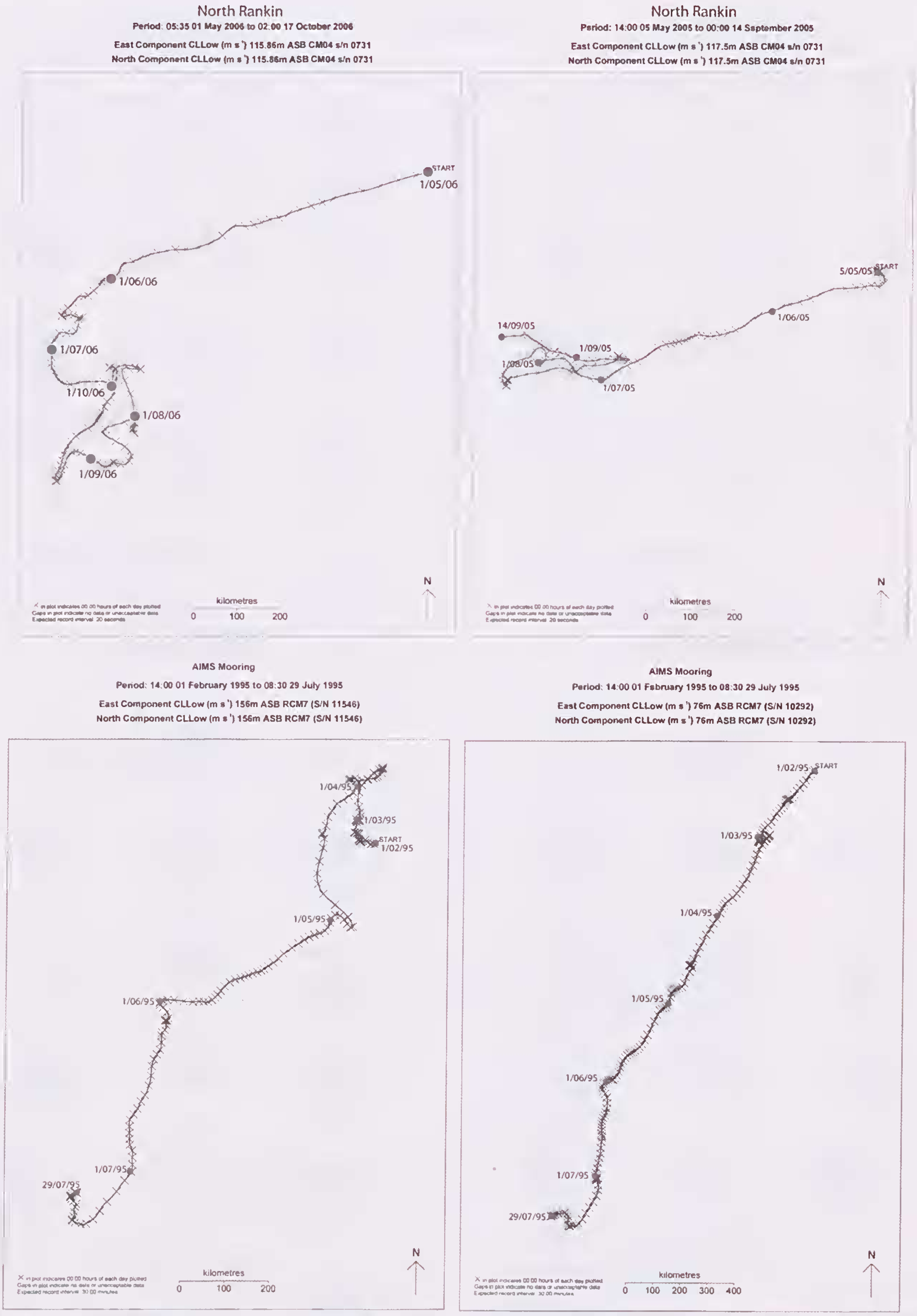


Titanichthys (at 225, ASB)
Combined Monthly
05:10 21 February 2004 to 22:35 25 March 2005



Titanichthys (at 235m ASB)
Combined Monthly
05:10 21 February 2004 to 22:40 25 March 2005





North Rankin
Period: 05:35 01 May 2006 to 02:00 17 October 2006
East Component CLLow ($m\ s^{-1}$) 115.86m ASB CM04 s/n 0731
North Component CLLow ($m\ s^{-1}$) 115.86m ASB CM04 s/n 0731

North Rankin
Period: 14:00 05 May 2005 to 00:00 14 September 2005
East Component CLLow ($m\ s^{-1}$) 117.5m ASB CM04 s/n 0731
North Component CLLow ($m\ s^{-1}$) 117.5m ASB CM04 s/n 0731

AIMS Mooring
Period: 14:00 01 February 1995 to 08:30 29 July 1995
East Component CLLow ($m\ s^{-1}$) 156m ASB RCM7 (S/N 11546)
North Component CLLow ($m\ s^{-1}$) 156m ASB RCM7 (S/N 11546)

AIMS Mooring
Period: 14:00 01 February 1995 to 08:30 29 July 1995
East Component CLLow ($m\ s^{-1}$) 76m ASB RCM7 (S/N 10292)
North Component CLLow ($m\ s^{-1}$) 76m ASB RCM7 (S/N 10292)

Figure 10. Continuous vector plots at (a) North Rankin at about 10 m depth showing a persistent south-westerly flow in May, and variable flow later, and (b) further north at the AIMS site, the flow at 100 m and 20 m depth is persistently south westwards for the period March to June.

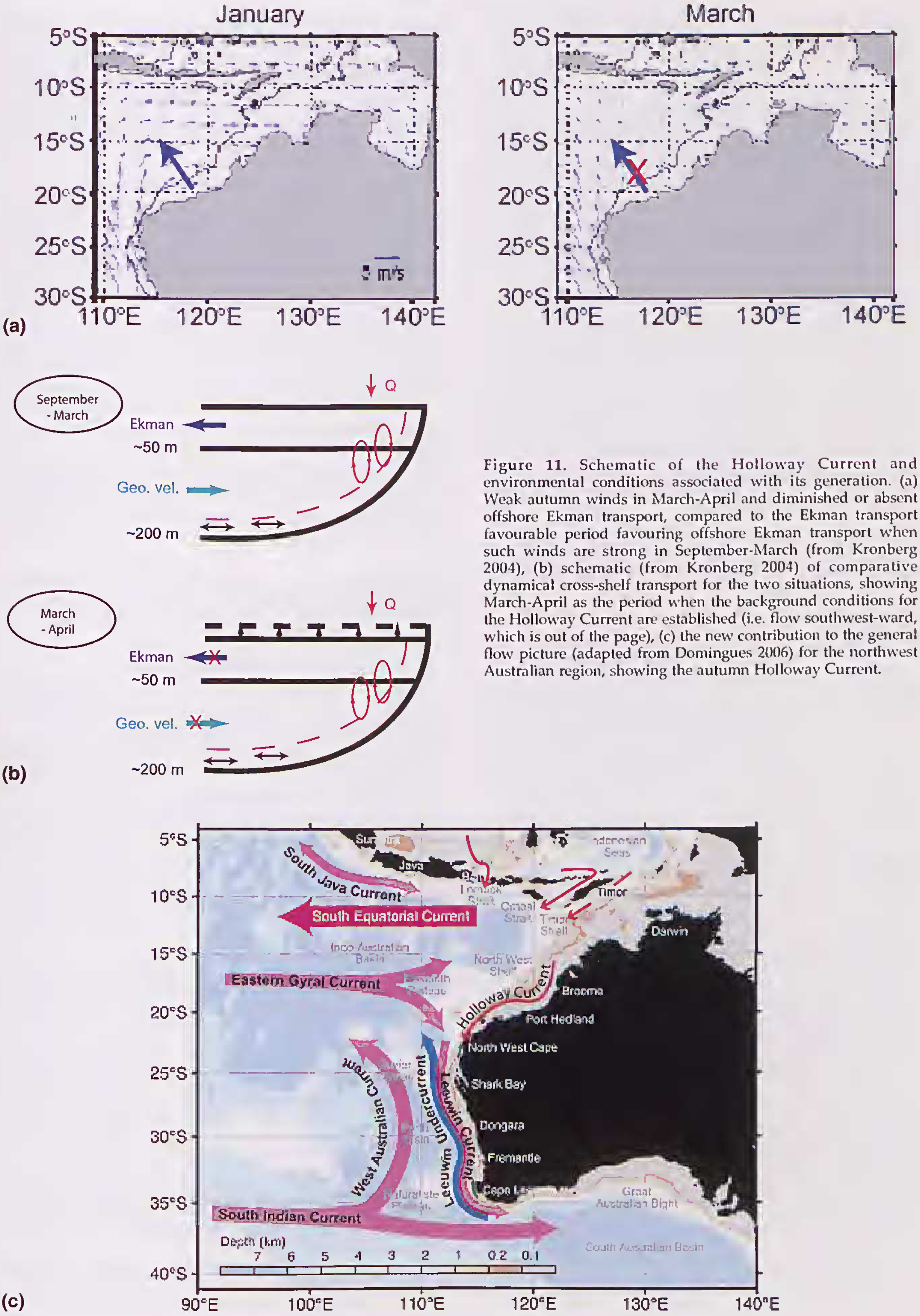


Figure 11. Schematic of the Holloway Current and environmental conditions associated with its generation. (a) Weak autumn winds in March-April and diminished or absent offshore Ekman transport, compared to the Ekman transport favourable period favouring offshore Ekman transport when such winds are strong in September-March (from Kronberg 2004), (b) schematic (from Kronberg 2004) of comparative dynamical cross-shelf transport for the two situations, showing March-April as the period when the background conditions for the Holloway Current are established (i.e. flow southwest-ward, which is out of the page), (c) the new contribution to the general flow picture (adapted from Domingues 2006) for the northwest Australian region, showing the autumn Holloway Current.

months, suggesting the cause to be southwesterly winds of sufficient strength to overcome the background steric height gradient.

In a subsequent study based on NW/SE oriented cross-shelf and slope transects of ADCP and CTD measurements centred at about 17° S and 19° S, Holloway (1995) found a distinct southwestward-flowing current in the months May and June. The current was broad (250 km at 17° S), at least 440 m deep and relatively weak (0.2 m s $^{-1}$), but the transport of about 4×10^{6} m^{3} s^{-1} is similar to the range of values for the main Leeuwin Current (Smith *et al* 1991). In the same study and based on moored current meter data in the Timor Sea (~ 12° S), Holloway (1995) reported a weak poleward flow for much of the year, but strongest from January to April.

Holloway & Nye's (1985) and Holloway's (1995) results were reinforced by the investigation of Kronberg (2004) on the seasonal circulation over the North West Shelf. This work discussed the overall variability of surface circulation and the vertical structure of integrated geostrophic flow under the action of wind, buoyancy and tide. Kronberg (2004) used *in situ* temperature data and current observations from 1999–2000 and altimeter data from TOPEX/POSEIDON to investigate the flow patterns over North West Shelf when warm water is supplied to the North West Shelf from the Arafura Sea. Kronberg (2004) concluded that during autumn, the absence of strong Ekman flow offshore allows the steric height over the shelf to build up due to local heating, causing a geostrophically-driven coastal flow towards the southwest over the North West Shelf. Kronberg referred to this feature as the Extended Leeuwin Current, consistent with the spirit of the conclusions drawn by Holloway & Nye (1985) and other studies since (Cresswell *et al*. 1993; Holloway 1995; Brink *et al*. 2007).

The recent study by Brink *et al*. (2007) examined two CTD and underway ADCP transects, at similar locations to those of Holloway (1995), at 16° S and 19° S. At the southernmost transect, shown in Figure 7, the along-isobath current (Figure 8) further confirms the existence of a southwestward current on the shelf slope. The current was weak (0.2 m s $^{-1}$) and at least 200 m deep. Further offshore a countercurrent, which was almost twice as strong, is also shown.

To supplement the previously collected data sets discussed above, we present current meter data collected at five locations (Figure 7) on or adjacent to the North West Shelf. These data were collected by RPS MetOcean and the Australian Institute of Marine Science in water depths varying from 67 to 350 m, during various periods between February 1995 and January 2007.

Monthly averaged current roses at various locations and depths shown in Figure 9 (North Rankin (water depth 125 m, instrument depths 8 and 35 m), Trunkline-KP (92 m, 34 and 46 m), Vincent (350 m, 10 and 60 m) and Titanichthys (250 m, 15 and 25 m) clearly show southwestward flow during the autumn months. At North Rankin the monthly averaged wind roses are also shown, indicating that the winds are weak in the autumn months, and blowing from the southwest against the current.

Continuous vector plots of currents at North Rankin (Figure 10) at about 10 m depth for two periods, May to September 2005 and May to October 2006, show predominantly southwestward flow during the months of May and June. In May 2006, the current speed was about 0.25 m s $^{-1}$, while in May 2005 the current speed was only 0.08 m s $^{-1}$. Further north, at the AIMS mooring (Figure 10), the flow at two depths, 20 m and 100 m, are also southwestward at speeds of about 0.12 m s $^{-1}$ and 0.08 m s $^{-1}$ respectively.

These findings are consistent with earlier results of other investigators (Holloway & Nye 1985; Holloway 1995; Brink *et. al*. 2007). We believe the mechanism driving this flow is the same as that reasoned by Kronberg (2004); *i.e.*, heating of the water column over the shelf, relatively weak winds allowing the heated water to be maintained over the shelf and not be otherwise replaced by upwellings of colder water, a consequent rise in steric height over the North West Shelf and, in turn, a geostrophic flow southwestward along the shelf. Whether this in fact represents a flow 'into' the head of the Leeuwin Current, or a seasonally occurring northward extension of where the Leeuwin Current actually starts, is open to interpretation.

We propose to formalise the name of this autumn current over the North West Shelf as the Holloway Current (Figure 11), in honour of the pioneering work by the late Dr Peter Holloway.

Acknowledgements: We thank Michael Garvey for assistance with producing some of the figures and Rita Reid for preparation of the text and figures of the final manuscript.

References

Akhir M F 2008 Physical processes along the southern continental shelf of Western Australia. Ph.D Thesis, The University of Western Australia, Nedlands, WA.

Bray N A, Wijffels S E, Chong J C, Fieux M, Hautula S, Meyers G & Morawitz W M L 1997 Characteristics of the Indo-Pacific throughflow in the eastern Indian Ocean. Geophysical Research Letters 24(21): 2569-2572.

Brink K H, Bahr F & Shearman R K 2007 Alongshore currents and mesoscale variability near the shelf edge off northwestern Australia. J. Geophys. Res 112, C05013, doi:10.1029/2006JC003725.

Cresswell G R, Boland F M, Peterson J L & Wells G S 1989. Continental shelf currents near the Abrolhos Islands, Western Australia. Australian Journal of Marine and Freshwater Research 40: 113-128.

Cresswell G R & Golding T J 1980 Observations of a south-flowing current in the southeastern Indian Ocean. Deep-Sea Research Part A: Oceanographic Research Papers 27: 449-466.

Cresswell G R, Golding T J, Boland F M & Wells G S 1985 Current measurements from sites near Abrolhos and Rottnest islands, Western Australia, 1973-75. Report. Division of Fisheries and Oceanography, CSIRO Australia.

Domingues C M 2006 Kinematics and heat budget of the Leeuwin Current. Ph.D Thesis. Flinders University, South Australia.

Domingues C M, Maltrud M E, Wijffels S E, Church J A & Tomczak M 2007 Simulated Lagrangian pathways between the Leeuwin Current system and the upper-ocean circulation of the southeast Indian Ocean. Deep-Sea Research Part II 54 (8-10): 797-817.

Feng M, Meyers G, Pearce A & Wijffels S 2003 Annual and interannual variations of the Leeuwin current at 32ºS. Journal of Geophysical Research – Oceans 108: 3355.

Feng M & Wijffels S 2002 Intraseasonal variability in the South Equatorial Current of the east Indian Ocean. J. Phys. Oceanogr. 32: 265-277.

Gentilli J 1991 Homologous peri-oceanic west coast climates in the southern hemisphere. Journal of the Royal Society of Western Australia 74: 15-34.

Gersbach G H, Pattiaratchi C B, Ivey G N & Cresswell G R 1999 Upwelling on the south-west coast of Australia – source of the Capes current? Continental Shelf Research 19: 363–400.

Godfrey J S 1996 The effect of the Indonesian throughflow on ocean circulation and heat exchange with the atmosphere: A review. J. Geophys. Res. 101: 12217-12238.

Godfrey J S & Ridgway K R 1985 The large-scale environment of the poleward-flowing Leeuwin current, Western Australia: longshore steric height gradients, wind stresses and geostrophic flow. Journal of Physical Oceanography 15: 481-495.

Godfrey J S & Mansbridge J V 2000 Ekman transports, tidal mixing and the control of temperature structure in Australia's northwest waters. J. Geophys. Res. 105: 24021-24044.

Godfrey J S & Weaver A J 1991 Is the Leeuwin Current driven by Pacific heating and winds? Prog. Oceanogr. 27: 225-272.

Hanson C E, Pattiaratchi C B & Waite A M 2005 Sporadic upwelling on a downwelling coast: phytoplankton responses to spatially variable nutrient dynamics off the Gascoyne region of Western Australia. Continental Shelf Research 25: 1561-1582.

Hatcher B G 1991 Coral reefs in the Leeuwin Current – an ecological perspective. Journal of the Royal Society of Western Australia 74: 115-128.

Holloway P E & Nye H C 1985 Leeuwin Current and wind distributions on the southern part of the Australian North-west Shelf between January 1982 and July 1983. Australian Journal of Marine and Freshwater Research 36: 123-137

Holloway P E 1995 Leeuwin Current observations on the Australian North West Shelf, May-June 1993. Deep-Sea Res. I, 42: 285-305.

IOC 1996 Sixth joint IOC-WMO meeting of IGOSS XBT Ship-Of-Opportunity programmes, Ottowa, Canada, 16-20 October 1995. IOC-WMO/IGOSS-XBT-VI/3. Intergovernmental Oceanographic Commission of UNESCO, 1 rue Miollis, 75015, Paris, France.

Kronberg M 2004 Ocean circulation over the North West Shelf of Australia – Does it impact on the Leeuwin Current? Ph.D Thesis, University of Copenhagen, Denmark.

Meyers G, Bailey R J & Worby A P 1995 Geostrophic transport of Indonesian throughflow. Deep-Sea Res. I 42: 1163-1174.

Nof D, Pichevin T & Sprintall J 2002 "Teddies" and the origin of the Leeuwin Current. Journal of Physical Oceanography 32 (9): 2571-2588.

Pattiaratchi C B 2006 Surface and sub-surface circulation and water masses off Western Australia. Bulletin of the Australian Meteorological Society 19: 95-103.

Pattiaratchi C B 2007 Understanding areas of high productivity within the south-west marine region. Report prepared for the National Oceans Office. School of Environmental Systems Engineering, University of Western Australia, Perth

Pattiaratchi C B & Buchan S J 1991 Implications of long-term climate change for the Leeuwin current. Journal of the Royal Society of Western Australia 74: 133-140.

Pearce A F 1991 Eastern boundary currents of the southern hemisphere. Journal of the Royal Society of Western Australia 74: 35-45.

Pearce A F & Cresswell G R 1985 Ocean circulation off Western Australia and the Leeuwin Current. CSIRO Division of Oceanography Information Service, Sheet No. 16-3, July 1985.

Pearce A F & Griffiths R W 1991 The mesoscale structure of the Leeuwin Current: A comparison of laboratory models and satellite imagery. J. Geophys. Res. 96: 16739-16757.

Pearce A F & Pattiaratchi C B 1999 The Capes current: a summer countercurrent flowing past Cape Leeuwin and Cape Naturaliste, Western Australia. Continental Shelf Research 19: 401-420.

Potemra J T, Hautala S L, Sprintall J & Pandoe W 2002 Interaction between the Indonesian seas and the Indian Ocean in observations and numerical models. Journal of Physical Oceanography 32: 1838-1854.

Quadfasel D & Cresswell G R 1992 A note on the seasonal variability of the South java Current. J. Goephys. Res. 97: 3685-3688.

Ridgway K R & Condie S A 2004 The 5500-km-long boundary flow off western and southern Australia. Journal of Geophysical Research – Oceans 109 (C04017), doi: 10.1029/2003JC001921.

Roberts C M, McClean C L, Veron J E N, Hawkins J P, Allen G R, McAllister D E, Mittermeier C G, Scgueler F W, Spalding M, Wells F, Vynne C & Werner T B 2002 Marine biodiversity hotspots and conservation priorities for tropical reefs. Science 295: 1280-1284.

Rochford D J 1969 Seasonal interchange of high and low salinity surface waters off south-west Australia. Technical Paper, Division of Fisheries & Oceanography.

Simpson C 1991 Mass spawning of corals on Western Australian reefs and comparisons with the Great Barrier Reef. Journal of the Royal Society of Western Australia 74: 85-92.

Smith R L, Huyer A, Godfrey J S & Church J A 1991 The Leeuwin current off Western Australia, 1986-1987. Journal of Physical Oceanography 21: 323-345.

Sprintall J G, Chong J, Syamsudin F, Morawitz W, Hautala S, Bray N & Wijffels S 1999 Dynamics of the South Java Current in the Indo-Australian basin, Goephys. Res. Lett. 26: 2493-2496.

Taylor J G & Pearce A F 1999 Ningaloo Reef Current observations and implications for biological systems: Coral spawn dispersal, zooplankton and whale shark abundance. Journal of the Royal Society of Western Australia 82: 57-65.

Telcik N 2004 Influence of the eastern Indian Ocean variability on south-west Australian rainfall. M.Sci. Eng. Thesis. The University of Western Australia. Crawley, WA.

Thompson R O R Y 1984 Observations of the Leeuwin current off Western Australia. Journal of Physical Oceanography 14: 623-628.

Thompson R O R Y 1987 Continental shelf–scale model of the Leeuwin current off Western Australia. Journal of Marine Research 45: 813-827.

Van Hazel J 2001 Physical oceanography of the Recherché Archipelago / Fitzgerald Biosphere area. Unpublished Honours thesis, School of Water Research, The University of Western Australia, Nedlands, WA.

Waite A M, Thomson P A, Beckley L E & Feng M 2007 The Leeuwin Current and its eddies. Deep Sea Research Part II Vol. 54, Numbers 8-10, 789-1140.

Weaver A J 1990 Ocean currents and climate. Nature Vol. 347, No. 6292: 432.

Wijffels S, Bray N, Huatala S, Meyers G & Morowitz W M L 1996 The WOCE Indonesian throughflow repeat hydrography sections: I10 and IR6. International WOCE Newsletter, 24: 25-28.

Wijffels S & Meyers G 2004 An intersection of oceanic waveguides: Variability in the Indonesian Throughflow region. Journal of Physical Oceanography, 34: 1232-1253.

Wijffels S E, Meyers G & Godfrey J S 2008 A twenty year average of the Indonesian Throughflow: regional currents and the interbasin exchange. Journal of Physical Oceanography (in press).

Wijffels S, Sprintall J, Fieux M & Bray N 2002 The JADE and WOCE I10/IR6 throughflow sections in the southeast Indian Ocean. Part 1: water mass distribution and variability. Deep-Sea Research Part II: Topical Studies in Oceanography 49: 1341-1362.

Woo M, Pattiaratchi C & Schroeder W 2006a Dynamics of the Ningaloo current off Point Cloates, Western Australia. Marine and Freshwater Research 57: 291-301.

Woo M, Pattiaratchi C & Schroeder W 2006 Summer surface circulation along the Gascoyne Continental Shelf, Western Australia. Continental Shelf Research 26: 132-152.

Woo M & Pattiaratchi C submitted Hydrography and water masses off the Western Australian coast. University of Western Australia, School of Environmental Systems Engineering reference SESE 094, Submitted to Deep-Sea Research I.